So, you want to know the speed of water

Spatial patterns of Transit-Time Distributions using ^{18}O-isotope tracer simulations at ungauged river locations

considered as a motorcar race

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Gentlemen, start your engines

In past studies, estimation of the speed of water vehicles (<u>*molecules*</u>) from Precipitation-Start to Outlet-Finish Line resulted in spatially-lumped vehicle rankings (<u>*Transit-Time Distributions, TTD*</u>). This was due to the need of inferring the actual number of vehicles in the race (<u>*effective precipitation*</u>); that is vehicles who do arrive at the monitored point without heat failure (<u>*evapotranspiration*</u>) nor lack of orientation (<u>*deep percolation*</u>) disqualifying them. Spatially-distributed TTDs need multiple gauging stations.

In close cooperation with the vehicle (t)racers (δ^2H and δ^{18}O), we present a method to estimate spatially-distributed TTDs, enabling a study of the faster and slower sections of a small speedway (<u>*catchment*</u>, *Fig. 6*).

The actual driver roster

From 6/6/2009 to 10/10/2011 several Race Events (<u>*precipitation events*</u>) happened at the 27 ha speedway "Wüstebach" in Germany (Fig. 4-6). Using the model TRANSEP, we were able to infer the actual number of race vehicles. Furthermore, we found that the race conditions of the speedway change from summer to winter season due to wetness conditions of the track (<u>*Mean Soil Water Content*</u>, Fig. 1, Tab. 1).

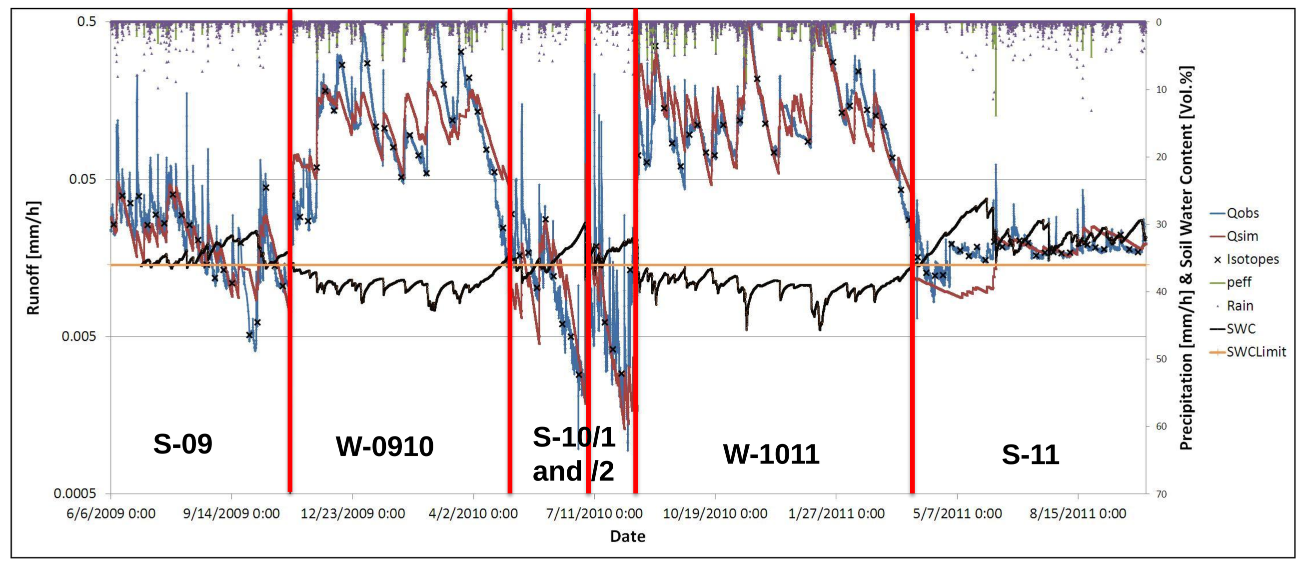

Fig. 1: Runoff simulation results for outlet gauging station 14 (Fig. 6). Simulated runoff Q_{sim} (red line) shows good comparison to observed runoff Q_{obs} (blue line) considering isotope sampling times (Isotopes, black crosses). The time series has been split-up in 6 different simulation periods (red vertical bars across graph) according to soil water content (SWC, black line). At 36 Vol.% SWC the catchment changes its hydrological behaviour. Effective precipitation (peff, green bars from top) has been derived from initial total precipitation (Rain, violet triangles from top) time series with Equation 1.

Season	S-09	W-0910	S-10/1	S-10/2	W-1011	S-11
Date	6/6/2009 - 10/31/2009	11/1/2009 - 4/30/2010	5/1/2010 - 7/3/2010	7/3/2010 - 8/15/2010	8/15/2010 - 3/31/2011	3/31/2011 - 10/10/2011
T_f [d]	4	19	2	2	7	37
T_s [d]	13	829	8	8	72	306
ϕ [-]	0.00	1.00	0.00	0.27	0.70	0.27
MRT [d]	9	15	6	4	7	77

Tab. 1: Parameter results for runoff simulation during Summer 2009, 2010 (part 1 and 2) and 2011 and Winter 2009/10 and 2010/11. $\mathbf{T_f}$ and $\mathbf{T_s}$ the fast and slow reservoir mean residence times, ϕ the fraction of fast reservoir contribution and mean response time (MRT) in days. Apparent is the drastically slow reaction of Summer 11 (see also Fig. 3). Switching parameter sets among winter and summer seasons show that winter seasons and Summer 09 & Summer 10/1 behave similar. This indicates equal dominant runoff generation processes.

Why do we see effects of cars before they arrive? (What is a Response Time?)

Entering of cars into the speedway at Precipitation-Start can cause fan waves reaching down to the Outlet-Finish Line due to sheer excitement (<u>*increased water pressure-head propagating through soil water to the outlet*</u>, Fig. 2).

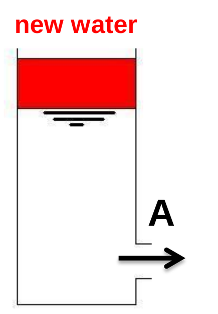

Fig. 2: Glass of water, as a very simple catchment model, with outlet **A**. Pouring red liquid on it will increase the outflow at **A**, but it won't be the red liquid coming out immediately. In other words: <u>the response time of the system is faster than the travel time of individual water molecules</u>.

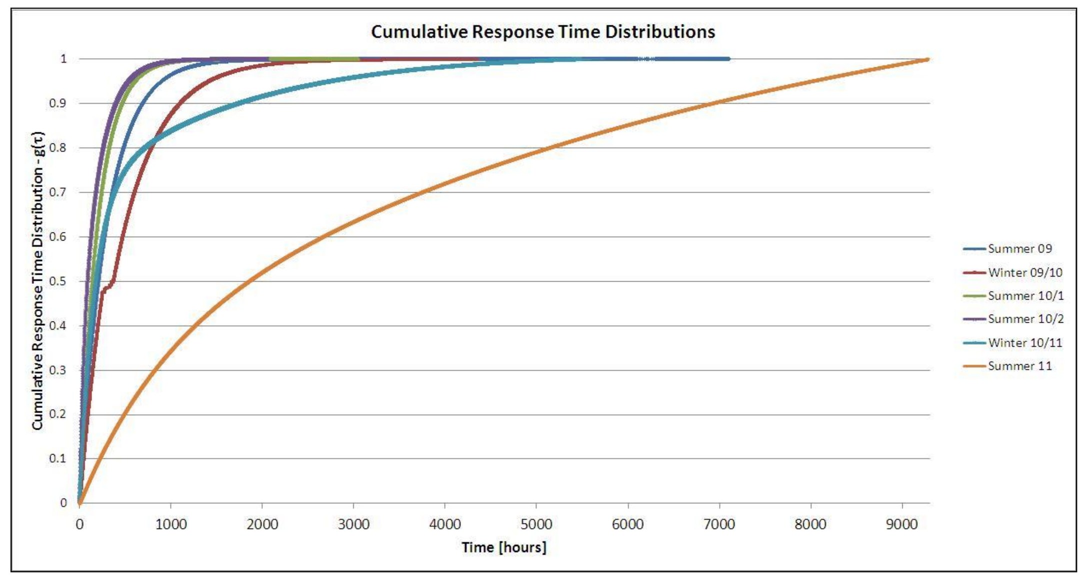

Fig. 3: Response Time Distributions (RTDs) of different seasons in the Wüstebach catchment with Two-Parallel Linear Reservoir model. Summer 11 (orange) plots vastly different from Summer 09 (blue) and 10 (violet & green), showing slower mean response times (MRT). Winter seasons plot approximately the same.

Mathematics of hydro*dynamic* vehicles (Convolution Function, Stream Isotope Concentration)

$$Q(t) = \int_0^t g(\tau)\, p_{\mathrm{eff}}(t-\tau)\, d\tau \qquad (1)$$

(1) Runoff at time t, Q(t), is simulated by integration of past effective precipitation events, $p_{eff}(t-\tau)$, with their corresponding response time, $g(\tau)$. Knowledge of Q(t) and total rainfall, p(t-τ), enables estimation of parameters for $p_{eff}(t-\tau)$ and $g(\tau)$ by inverse modeling. Optimization algorithm used was the Ant Colony Optimization (ACO), with Volumetric Error (VE) as the objective function.

$$C(t) = \frac{\int_0^t C_{\mathrm{in}}(t-\tau)\, p_{\mathrm{eff}}(t-\tau)\, h_b(\tau)\, d\tau}{\int_0^t p_{\mathrm{eff}}(t-\tau)\, h_b(\tau)\, d\tau} \qquad (2)$$

(2) Known stream isotope concentrations at time t, C(t), are simulated with input data of isotopes in precipitation, $C_{in}(t-\tau)$, effective precipitation, $p_{eff}(t-\tau)$ and transit time distribution $h_b(\tau)$. ACO was used again as the optimization algorithm and Nash-Sutcliffe Efficiency (NSE) as the objective function.

Geographic Location

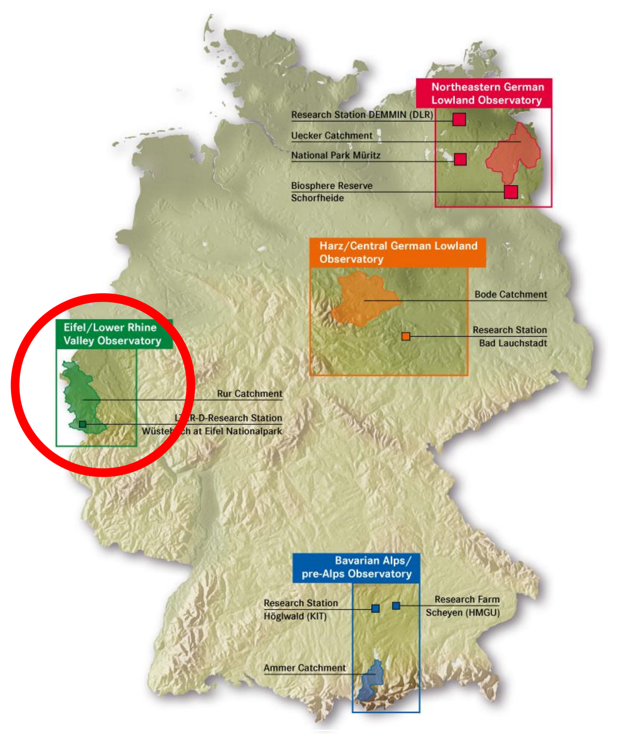

Fig. 4: TERENO (Terrestrial Environmental Observatories) test sites, with Eifel/Lower Rhine Valley highlighted.

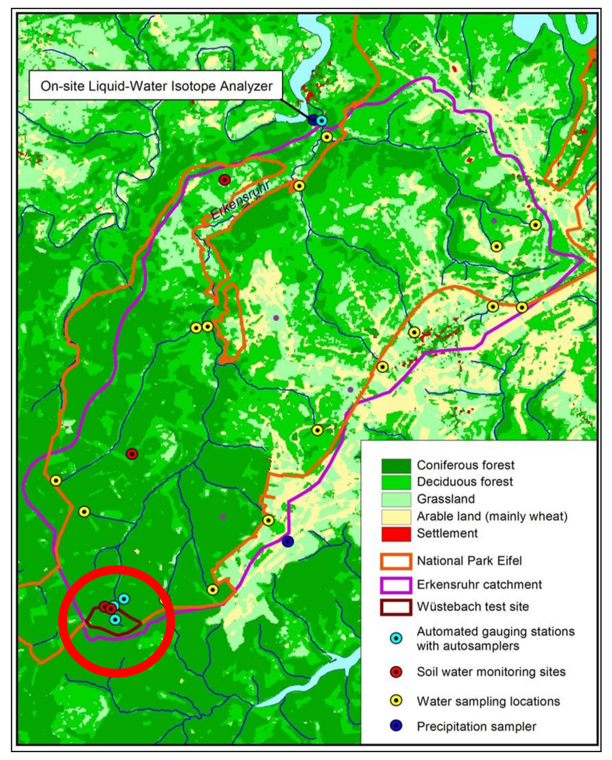

Fig. 5: Erkensruhr catchment (45 km^2), with Wüstebach sub-catchment highlighted.

Speedway Map & Race Results

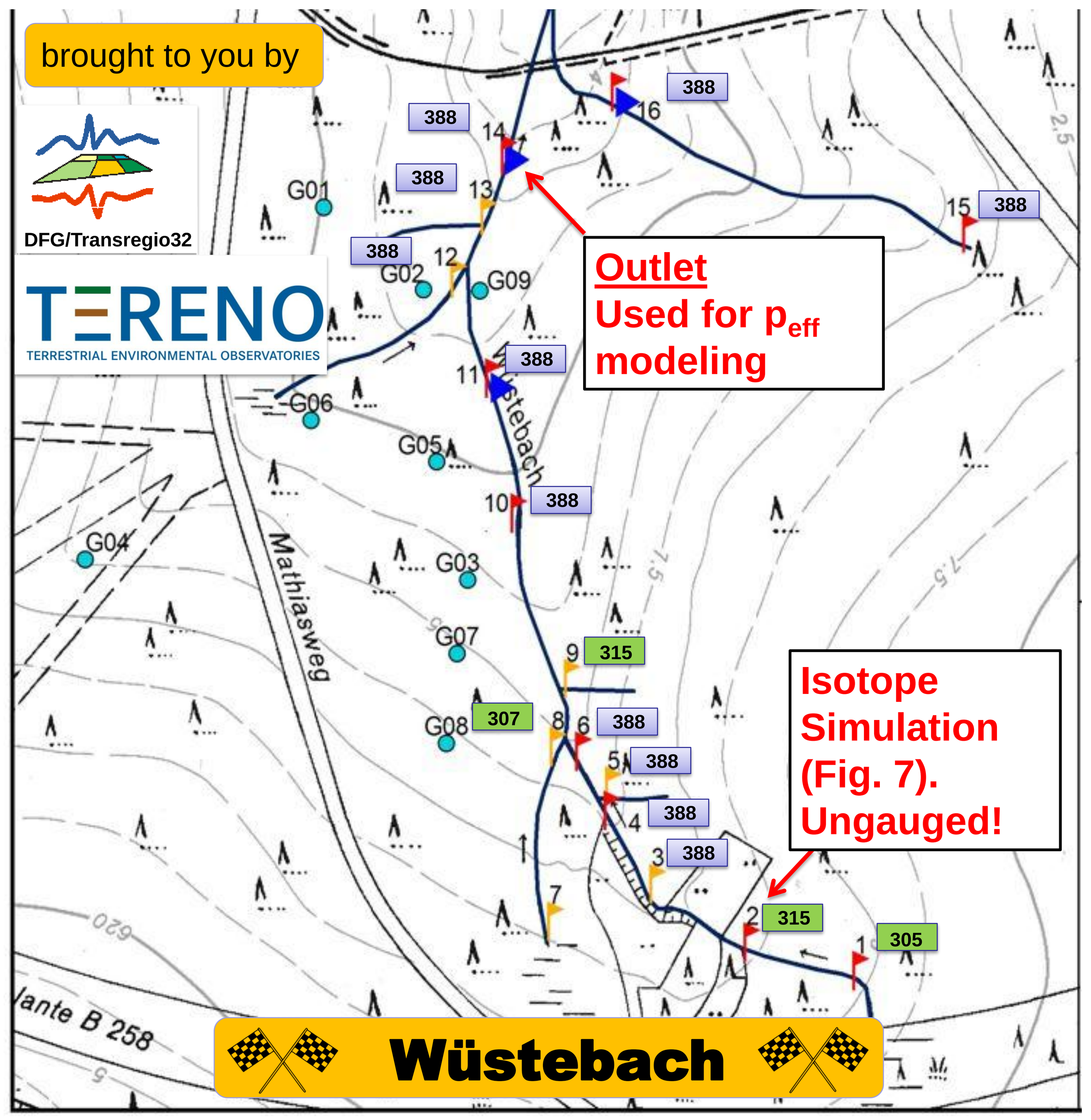

Fig. 6: Wüstebach catchment measurement network with stream (1-16, yellow and red flags) and groundwater (G01-G09, turquoise dots) sampling points, as well as three gauging stations (blue, sideways triangles). <u>Results shown are preliminary</u>.

GO!!!

Modeling of weekly isotope (t)racer time series from 16 monitoring locations along the stream resulted in calibrated TTD estimates. However, modeling results need to be corrected in a two-step process for influence of plant abuse (<u>*canopy evaporation*</u>) and confusion due to heat (<u>*soil evaporation*</u>), rendering the (t)racers **non-conservative** and slightly confused.

Plant abuse can be overcome by adding 0.3‰ to all input (t)racers in precipitation, simulating times with temperatures below 0°C well. Heat confusion of (t)racers is battled by a linear regression of mean daily air temperature and mean daily residual between observed and modeled (t)racers.

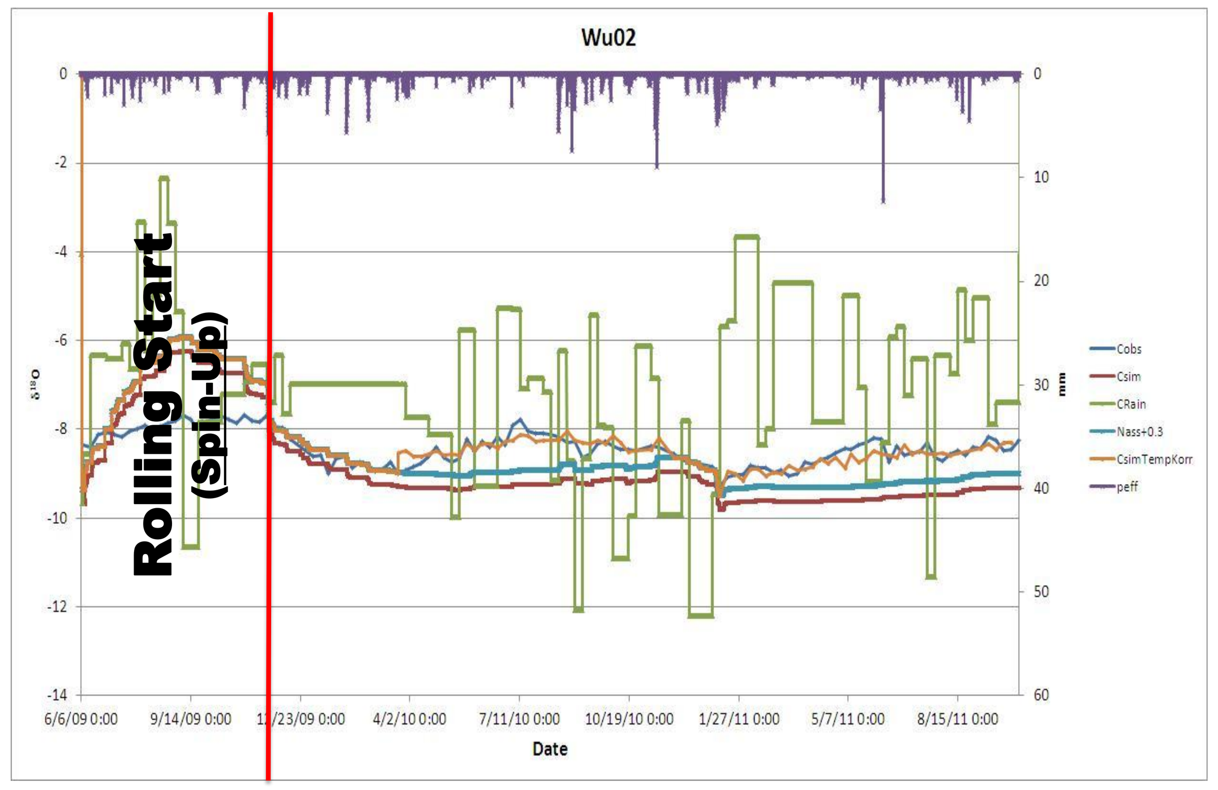

Fig. 7: Initial simulation result (Csim, red line) of observed isotopes (Cobs, blue line) for point 2 on the map. Correction for canopy evaporation by adding 0.3 ‰ (Nass+0.3, turquoise line) and subsequent correction for soil evaporation by temperature-residuals regression (CsimTempKorr, orange line). Green line depicting isotope in precipitation as input and violet bars from top the effective precipitation time series.

§ Sport Regulations § (Limitations and Assumptions)

- Vehicle drop-out rate is constant (constant p_{eff} over catchment) - **Assumption**
- Method limited to small speedways (catchments) - **Limitation**
- Conceptual model (TRANSEP) not able to fully simulate non-linear behavior of catchment

Acknowledgment to Transregional Collaborative Research Centre 32 (TR32; more information at http://www.tr32.de) and the Field and Laboratory Team of the IBG-3 Institute